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Optimization of Water Flooding Strategies in Offshore Fractured Reservoirs

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ABSTRACT: In order to clarify the water flooding development and production characteristics of offshore fractured reservoirs and optimize the reasonable water flooding rate and water flooding mode, a laboratory physical model displacement experiment is designed to optimize the water flooding simulation experiment based on the principle of similarity criteria and with reference to the actual injection-production well pattern, reservoir and fluid parameters of offshore Oilfield A. The experimental results show that the fractured reservoir has a longer water-free oil production stage under the influence of imbibition action when the matrix system is saturated with crude oil, compared with the case of unsaturated crude oil in the matrix system. When production stage enters the medium water cut stage, there will be a continuous stable water cut stage; The lower the flooding rate is, the longer the water-free oil production stage is and the higher the ultimate oil recovery is. With the increase of flooding rate, the water cut rises slowly at the early stage of water breakthrough, but the stable production stage at high water cut stage is shortened. Compared with continuous water flooding, intermittent water flooding after entering high water cut stage can promote the imbibition of matrix system, thus increasing the cumulative oil production and enhancing oil recovery by 3. 3%.

KEYWORDS: Imbibition, Flooding Rate, Intermittent Water Flooding, Fractured Reservoir, Offshore Oilfield.

I. INTRODUCTION

The storage system of fractured reservoir includes dual systems of fracture and matrix. Affected by the geological conditions of reservoir formation, the development scale, development characteristics and regularity of fractures in the reservoir are not strong, so that although the fracture system has high permeability, it is also accompanied by strong heterogeneity, which makes the reservoir prone to water flooding breakthrough in the process of water flooding development [1]-[5].The matrix system is an important medium for crude oil storage with high porosity, but the permeability is very low, so the crude oil in the matrix system needs to enter the fracture system through imbibition, and then seepage to the production well in the fracture. At present, there are many studies on the imbibition mechanism and influencing factors of matrix system [6]-[9], but there are few studies on the influence of matrix imbibition on the whole development and production process. Only by understanding the development characteristics can the subsequent optimization of development scheme be more targeted, so it is necessary to carry out relevant studies.

Fracture system is the main channel for crude oil seepage to the wellbore of production wells. Some studies have pointed out that high productivity and long water-free oil production stage can be obtained by natural energy development in the early stage of development of fractured reservoirs. However, with the development, if the reservoir energy is not supplemented by water flooding in time, there is a risk of fracture closure due to insufficient energy. The reservoir will lose the main seepage channel, so that the liquid production of the production well will be greatly reduced, and a higher recovery factor will not be obtained [10]-[11]. offshore oilfield A is a fractured reservoir, the oilfield is developed by artificial water flooding, and the three-dimensional interactive well pattern of horizontal bottom injection and top production is adopted. At present, the recovery percent is more than 25%, and it will enter the high water cut stage. In recent years, the decline rate of production is high due to the increase of water cut. At present, most of the reservoir optimization water flooding schemes that can be used for reference are mainly onshore conventional sandstone reservoirs [12]-[13], and there are few studies on offshore fractured reservoirs [14]-[16].In order to improve the development effect

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of oilfield, it is necessary to study the optimal water flooding in fractured reservoirs.

II. EFFECT OF MATRIX IMBIBITION ON PRODUCTION DYNAMIC

a. EXPERIMENTAL DESIGN

In order to study the role of matrix imbibition in the production of fractured reservoirs, water flooding experiments are designed to be conducted at the same flooding rate under the conditions of saturated crude oil and unsaturated crude oil in the matrix system, and the specific experimental parameters are shown in Table 1.

Table 1 Comparison of Experimental Parameters of Saturated/Unsaturated Crude Oil in Matrix System

Experiment Number	Model saturated crude oil condition	Oil volume in the fracture system, mL	Oil volume in the fracture matrix system mL	Total oil volume mL
1	Fracture-only system saturated oil	652	0	652
2	The matrix and fracture system are saturated with crude oil	648	685	1333

The injection-production well pattern simulates the three-dimensional interactive horizontal well pattern of the actual bottom injection and top production in the oilfield, as shown in Figure 1. The experimental steps are as follows: (1) filling a model rock block and an injection-production well pattern, and connecting an experimental device; (2) measure that saturated oil volume of the matrix/fracture system for the saturate oil of the matrix/fracture system; (3) carrying out water flooding at the flooding rate of 1mL/min, measuring the liquid production, oil production and water cut at the outlet end, and flooding until the water cut is 98%, and ending the group of experiments; (4) take out that rock block in the model, putting the rock block into a drying oven for a certain time, evaporate the water in the rock block, and returning to the step (1) to carry out the next group of experiments.

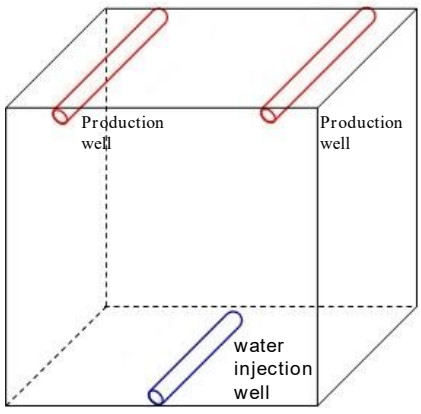

Fig. 1 Schematic diagram of injection-production pattern in 3D experimental model

b. ANALYSIS OF EXPERIMENTAL RESULTS

It can be seen from the relationship between water cut and recovery percent (Fig. 2) that no matter whether the matrix system is saturated with crude oil or not, the rising trend of water cut after water breakthrough can be divided into two stages, the first stage is the rapid rising stage at the early stage of water breakthrough, and the second stage is the slow increasing stage at the middle and high water cut stage. Further comparison shows that the rising rate of water cut in the first and second stages of the matrix system with unsaturated oil is significantly higher than that with saturated oil.

The main reason for the above development and production performance characteristics and the difference between the two groups of experiments is that the fracture permeability in the three-dimensional physical model is very large, which has reached the Darcy level. Therefore, no matter whether the matrix system is saturated with oil or not, the seepage of injected water in the fracture is very average, and the oil-water interface rises smoothly. Once the oil well has water, the degree of water flooding will increase rapidly, and the water cut will rise rapidly. However, when the matrix system is saturated with crude oil, the matrix system supplies oil to the fracture system through imbibition action, which not only prolongs the water-free production stage, but also slows down the rising speed of water cut after breakthrough.

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When the production stage enters the high water cut stage, the water flooding degree of production wells tends to be stable when it reaches a certain degree, and the water cut rises slowly, but because of the high sweep degree of injected water in the fracture system at this stage, the saturation difference between the fracture system and the matrix system reaches the maximum when the matrix system saturates crude oil, and at this time the imbibition oil production capacity of the matrix is the strongest. In the second experiment group, the rising speed of water cut was significantly slowed down after entering the middle and high water cut stage, and the oil production by imbibition could be maintained for a long time due to the high crude oil reserves in the matrix system. It was shown that the second group of experiments maintained a continuous stable stage of water content after entering the middle water cut stage.

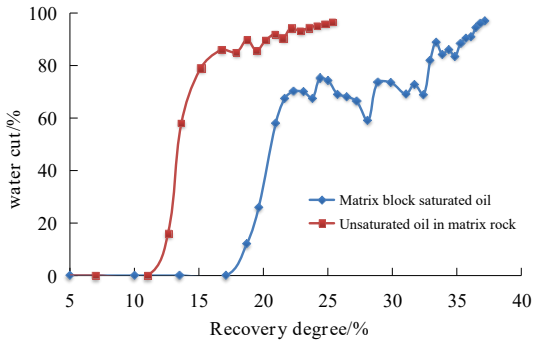

Fig. 2 Relationship between recovery degree and water cut when matrix system is saturated/unsaturated crude oil

III. EFFECT OF DIFFERENT FLOODING RATES ON PRODUCTION CHARACTERISTIC

a. Experimental Design

In order to study the influence of different flooding rates on the production characteristics of fractured reservoirs, in the three-dimensional model experiment, three flooding rates of high, medium and low are taken: 2.00 mL/min, 1.00 mL/min and 0.35 mL/min, which are labelled as experiment 3, 4 and 5 respectively, and the three flooding experiments are carried out in turn. The experimental procedure is basically the same as the first experiment in this research.

b. Analysis of Experimental Results

It can be seen from the relationship curve between recovery degree and water cut (Fig. 3) that the lower the flooding rate is, the longer the water-free oil production stage is. This is mainly because when the flooding rate is low, the shape of oil-water interface is stable and the rise rate is slow, and the area swept by the flooding water in the vertical direction is large, so the water-free oil production stage is longer. With the increase of the flooding rate, the oil-water interface rises in a "cone" shape. When the top of the water cone reaches the production well, a breakthrough will be formed, and the water-free oil production stage will be shortened.

From the dynamic characteristics of the curve, the lower the flooding rate is, the faster the water cut rises at the initial stage of water breakthrough, and after reaching the medium-high water cut stage, the relatively stable water cut stage, that is, the stable production stage, is longer. This is because in the process of displacement, the matrix system always supplies oil to the fracture system at a certain rate. When the flooding rate is low, the oil supply and liquid production of the matrix reach a relatively stable state when the water cut rises to a certain extent, so there will be a stable production stage of water cut in the middle and high water cut stage. With the increase of flooding rate, the water cut rises slowly at the early stage of water breakthrough, but the stable production stage at the high water cut stage is shortened, and the water cut continues to rise to 98% after entering the middle and high water cut stage. This is because when the flooding rate is low, the oil-water contact rises smoothly, and the degree of recovery is high when water breakthrough occurs, especially when the degree of recovery of fractures is very high, the degree of water flooding of production well is also high at this time. Therefore, although the matrix supplies oil to fractures through imbibition at this time, it cannot offset the state of strong water flooding of production well, resulting in the rapid increase of water cut.

When the flooding rate is relatively high, the oil-water contact rises like a cone, the oil recovery of the fracture system at water breakthrough is not high, and the degree of water flooding of production well is also low. At the same time, due to the high flooding rate, the water saturation in the fracture system rises faster, and the saturation difference between the matrix system and the fracture system is established faster, which makes the imbibition of the matrix system proceed at a faster speed from the beginning. At the initial stage of water breakthrough, the matrix system continued to produce crude oil under strong imbibition, which made the water cut rise slowly at the initial stage of water breakthrough. However, due to the high flooding rate, the injected water is difficult to be swept by water flooding in the

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unswept area after the breakthrough of the production well, resulting in a short stable stage of water cut and a low ultimate recovery rate after entering the medium-high water cut stage.

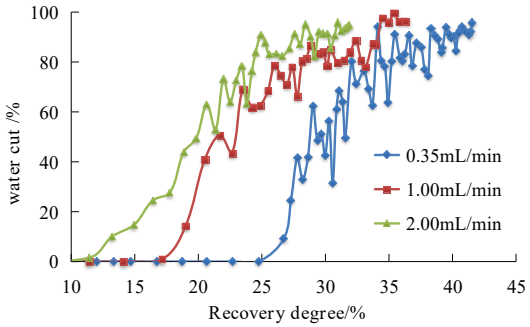

Fig. 3 Relationship between recovery percent and water cut at different flooding rates

Considering that the service life of offshore oil production platform is generally 35 to 45 years, the water flooding optimization study needs to compare the production time of each scheme. As shown in Figure 4, under the condition of low flooding rate of 0.35 mL/min (Experiment 3), it takes 3186 minutes to reach the limit water cut of 98%, and the final recovery rate is 41.5%.In the case of medium flooding rate of 1.00 mL/min (Experiment 4), it takes 1263 min to reach the limit water cut of 98%, and the final recovery is 36.4%.Although Experiment 3 can achieve higher recovery, it takes 2.52 times as long as Experiment 4, and the recovery is only 1.14 times as long as Experiment 4.Up to the recovery percent of 36.4% (recovery factor of experiment 4) in experiment 3, the time spent was 1780 min, which was still 1.41 times of that in experiment 4.Therefore, Experiment 4 has the advantage of development time, such as converting to actual development and production, which is more conducive to recovering the development investment of the oilfield as soon as possible. In the case of high flooding rate of 2.00 mL/min (Experiment 5), the recovery rate is lower, only 31.9%. The optimum displacement velocity is determined as the medium displacement velocity by comprehensive judgment.

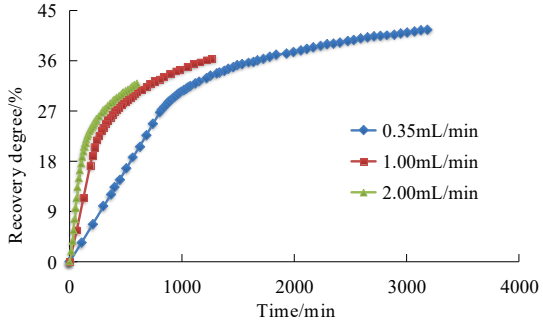

Fig. 4 Relationship between displacement time and recovery percent at different flooding rates

IV. EFFECT OF DIFFERENT FLOODING RATES ON PRODUCTION CHARACTERISTIC

a. Experimental Design

In order to study the influence of water flooding mode adjustment on production performance of fractured reservoirs in high water cut stage, two groups of experiments were designed, including conventional continuous water flooding (experiment 6) and two cycles of replacement intermittent water flooding in high water cut stage (experiment 7), with a flooding rate of 1.00 mL/min. In experiment 6, the flooding was stopped when the water cut was 96%; in experiment 7, on the basis of experiment 6, the well was shut in for 30 minutes, and then the displacement continued until the water cut was 96% after the well was opened, that is, the first intermittent cycle, and then the well was shut down in for another 30 minutes, and continued to the water cut after the well opened, that is, the second intermittent cycle.

b. Analysis of Experimental Results

According to the change of water cut in Experiment 6 and Experiment 7 (Fig. 5), it can be seen that the water cut decreases significantly when the well is shut down in high water cut stage and then opened for production. With the production, the water cut gradually rises to 96%.This is because after the well is shut in, the oil and water in the reservoir are redistributed, the cone shape of the oil-water contact falls back, and the degree of water flooding of the oil well is reduced, so that the wave area of the injected water in the system is increased, and at the same time, the matrix system continuously supplies oil to the fracture system through imbibition. Therefore, when the well is opened for production, the oil production increases and the water production decreases, showing a decrease in water cut. The water cut of the production well returned to 96% after 50 minutes of production in

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the first intermittent stage. The water cut of the production well returns to 96% after 45 minutes of production in the second intermittent stage, mainly because the overall water flooding degree of the model is strong at this time, and the remaining oil is gradually reduced, so that the intermittent stage is gradually shortened.

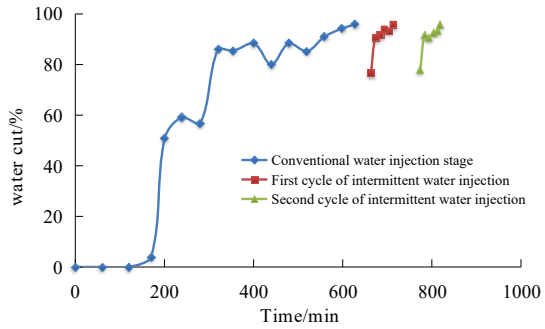

Fig. 5 Water Cut Variation of Conventional/Intermittent Water flooding

According to the change of cumulative oil production curve of the two groups of experiments (Fig.6), compared with the conventional continuous water flooding, the cumulative oil production of intermittent water flooding in high water cut stage is significantly increased, in which the cumulative oil production of the first intermittent stage is increased by 18.81 mL, and the oil recovery is increased by 2.2%. In the second intermittent cycle, the cumulative oil production increased by 8. 96 mL, and the recovery factor increased by 1. 1%. The total recovery factor of the two intermittent cycles is increased by 3.3%, and the development effect is improved obviously.

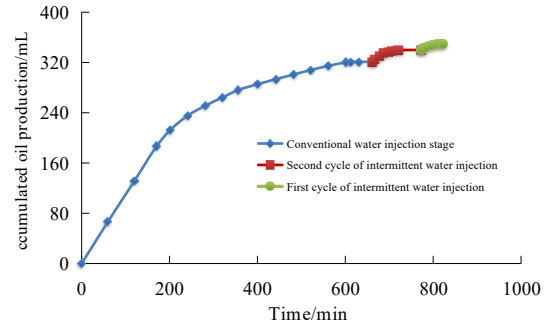

Fig. 6 Cumulative Oil Production Change of Conventional/Intermittent Water flooding

V. CONCLUSION

Under the influence of imbibition, the matrix system continuously supplies crude oil to the fracture system, which makes the fracture reservoir have a longer water-free oil production stage, and there will be a continuous water-cut stable stage after the development enters the medium water-cut stage.

The lower the flooding rate is, the longer the water-free oil production stage is and the higher the ultimate oil recovery is. With the increase of flooding rate, the water cut rises slowly at the early stage of water breakthrough, but the stable production stage at the high water cut stage is shortened. For offshore oilfields, the optimization of flooding rate should be considered in combination with the service life of specific production facilities and economic recovery stage.

After the reservoir production enters the high water cut stage, the intermittent water flooding mode is changed from the conventional continuous water flooding mode, which can give full play to the imbibition effect of the matrix system and improve the recovery rate by 3.3% compared with the conventional continuous water flooding. It is suggested that the intermittent water flooding mode be adopted after the offshore Oilfield A enters the high water cut stage.

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